Arid Land Research and Management, 20:133–146, 2006

ISSN: 1532-4982 print/1532-4990 online
DOI: 10.1080/15324980500546007

Carbon Sequestration in a Savannah Soil in Southwestern Burkina as Affected by Cropping and Cultural Practices

E. Hien

Institut de l'Environnement et de Recherches Agricoles (INERA), Burkina Faso

F. Ganry
R. Oliver

Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Laboratoire Matières Organiques des Sols Tropicaux (MOST), Montpellier, France

Soil organic matter (SOM) plays a dominant role in soil fertility and in the reduction of greenhouse gas emissions. The way in which land is managed directly influences SOM. The objective of this work was twofold: (1) to evaluate the potential storage of C in a plinthic luvisol in southwest Burkina Faso under three different management methods—natural savannah vegetation, continuous cropping without manure and continuous cropping with manure; and (2) to examine the factors (chemical, physical and management) determining C storage in the soil. The methodology used in the field was characterization of the environment by soil mapping, measurement of bulk density, and soil sampling. In the laboratory, the determination of the soil physical and chemical characteristics and measurement of C and N contents and particle size distribution of the SOM were accomplished. The results show that the C content in the top 30 cm was 61 Mg ha^{-1} under savannah as compared to 16 Mg ha^{-1} under continuous cropping, with the C being present mainly in the surface layer. Cow manure applied at 2 Mg DM ha^{-1} yr^{-1} for 13 years led to an increase of 9 Mg C ha^{-1}. Particle size analysis showed that: (a) the carbon content was highest in the clay size fraction, and (b) the method of soil management mainly influenced the C content of the coarse fractions (200–2000 μm) and the fine fractions (0–20 μm) at the surface.

Keywords soil carbon, Burkina, savannah, continuous cropping, manure

It is now well established that the characteristics of the soil organic matter (SOM) are related to the soil and bioclimatic environment on the one hand and to soil management practices on the other (Sanchez et al., 1989). Any modification of one or the other affects these characteristics and consequently the processes which influence the cycling and balances of the major elements, including C (Volkoff et al., 1989; Eswaran et al., 1993; Feller, 1994; Bernoux et al., 1998; Shang & Tiessen, 1998; Hien,

Received 6 September 2005; accepted 22 November 2005.
Address correspondence to Dr. F. Ganry, CIRAD, TA 40/01. Avenue Agropolis, 34 398 Montpellier cedex 5. France. E-mail: francis.ganry@cirad.fr

2004), together with the water dynamics, and gaseous and heat exchange within the soil (Pieri, 1989; Batjes, 1996). Clearing land, particularly the replacement of a perennial cover by annual crops, by modifying the amount and distribution of plant growth, results in the lowering of C contents (Lundgren, 1978; Detwiler, 1986; Houghton et al., 1991; van Noordwijk et al., 1997).

The SOM has two major functions. At the local level, the SOM is an essential factor in the fertility of cultivated soils, and at the global level, soils represent a major reserve of terrestrial C, with the world C mass estimated at 1200–1600 $\times 10^{15}$ g of C (Eswaran et al., 1993; Batjes, 1996; Zech et al., 1997; Arrouays et al., 2002). The estimation of organic C stocks of soils is necessary to evaluate the impact of soil management on greenhouse gas emissions. Feller & Beare (1997) showed the importance of the characteristics of SOM as determinant of SOC storage: aggregated particles of different size and particles-size fractions; these last characteristis may be particularly important in tropical soils where 20 to 40% of the SOC is associated with sand-size fraction as compared to 2 to 14% for many temperate soils.

The southwest region of Burkina Faso, the subject of the present study, is the most favorable part of Burkina Faso for the production of biomass: relatively dense savannah vegetation combined with over 1000 mm rainfall yr^{-1}. However, since the 1970s, migration from the north of the country and current soil management practices (notably grubbing out trees, burning and shifting cultivation) have degraded this ecosystem and have resulted in decline of soil C (Pieri, 1992). Starting from this observation and also from present knowledge of the dynamics of the SOM and sites representative of the agro-ecosystem, our objective was to evaluate the soil organic C (SOC) storage potential in native savannah and, on this basis, to evaluate the impact of more than 10 yr of cultivation without or with manure, (quantitative assessment), and secondly, to understand the factors affecting SOM change (qualitative assessment).

Materials and Methods

Geographical Context

This study was carried out in the southwestern part of Burkina Faso, in the province of Poni (9°30′–10° 40′ N, 2°40′–3° 50′ W) which belongs to the Sudanese meridian ecological sector (Guinko, 1998). The annual rainfall of between 900 and 1000 mm is unimodal. The temperature regime is characterized by extreme fluctuations; the mean annual temperature is about 28°C; but the mean low temperatures are observed in January (16.5°C) and the highest in March (38.4°C). Evapotranspiration (Penman) mean values fluctuate from 121 mm (August) to 205 mm (March). The geological formations are dominated by an expanse of crystalline rocks (granite and granite-like), (BRGM, 1992).

The soils are dominated (60%) by the class known as iron and manganese sesquioxide soils, mainly of the compacted subgroup (CPCS, 1967), plinthic luvisols or plinthic acrisols according to the World Reference Base (FAO et al., 1999).

Experimental Design

The experimental layout was based on plots on peasant farms belonging at the same soil unit. The soil unit required the following specifications: the same pedogenesis and particle size characteristics, the same natural vegetation, and the same landscape

position. To permit comparison between plots, several soil pits were dug by plot (see further in "Characterising the physical environment and the soils" section). Each plot of 1 ha each is also defined by a main soil management regime and was situated below a hard-pan plateau, on a high slope at Librira, 6 km south of Loropéni.

Savannah Site
This natural vegetation is a fairly dense bushy and wooded savannah consisting of *Isoberlinia doka*, *Combretum glutinosum*, *Piliostgma thonningii and reticulatum*, *Parkia biglobosa*, *Vitellaria paradoxa*, *Parinari curatellifolia*, *Entada africana*, *Lannea acida*, *Gardenia erubescens*, *Diospyros mespiliformis*, *Tamarindus indica*, *Serincanthe chevaleri*, with a ground flora of *Andropogon gayanus*, *Pennisetum pedicelatum et Loudetia togoensis*. Having not been cultivated for more than 30 years, this savannah is communally grazed and intentionally subjected to bush fires once a year at the start of the dry season.

Cropped Site Without Applied Manure
This was a field cropped for 13 years, with maize the first three years and since with millet (*Pennisetum typhoïdes*) with fairly poor yields (500 kg ha^{-1}). The field was annually mould-board ploughed to an average depth of 10 cm. No fertilizer was applied. All crop residues were removed from the fields for domestic purposes; the stems of sorghum or millet for example are used firstly for combustion, comes then the food for the animals in the farm and lastly the stems are use for construction of fences of gardens. But one should not neglect the consumption of the stems in the fields by the animals which digress during the dry season (Dugué, 1993; Dugué, 1994).

Cropped Site With Manure Applied
This field received an annual dressing of 2 Mg DM ha^{-1} of cow manure. Half was sown with maize (*Zea mays*, SR21) and the other half with sorghum (*Sorghum bicolor*, Wedzouré) each of 13 yr in a maize-sorghum rotation. The average yields were 1000 kg ha^{-1} for sorghum and 2000 kg ha^{-1} for maize.

Characterizing the Physical Environment and the Soils

Our objective was to find a soil unit representing the above three treatments to enable comparison of the effects of soil management. To do this, 50 soil pits were dug to a depth of 120 cm across the three management treatments: 15 in the savannah plot, 15 in the unmanured crop plot, and 20 in the manured crop.

Each plot was 1 ha in size. These soils and their environment were described and 12 profiles (four by plot or treatment) were chosen using the method known as *Line transect reflection methodology* (Mckenzie et al., 2000). The principle of the method consists of choosing a random starting point on the study site and tracing transects (at least three) of a given length and according to a predetermined geometry. Observations are made along these transects. Three pits (solum) by plot are subsampled for physochemical analyses of soils.

The three horizons (A, Bt1, and Bt2) of each solum were sampled. Bulk density was measured in all the pits using an in situ membrane densitometer. The C and N stocks (Mg ha^{-1}) of a nongravely layer of thickness "e" (dm) with C and N contents

($mg\,g^{-1}$ of soil) and whose bulk density is "ap" ($g\,cm^{-3}$) were calculated using the formula:

$$C, N(Mg\,ha^{-1}) = C, N(mg\,g^{-1} of\ soil) * ap(g\,cm^{-3}) * e(dm)$$

Physicochemical Characterization of Soils

The following determinations were made: particle size (coarse sand, fine sand, coarse silt, fine silt and clay), pH water and KCl (using NF ISO 10390 method), carbon and nitrogen, with CHN method, CEC using cobalt method (NF X 31130) and available phosphorus according to Olsen Dabin method. In addition to these classical determinations, particle size fractionation of the OM was done for the fractions 200–2000 μm (A), 50–200 μm (B), 20–50 μm (C) and 0–20 μm (D), using the method developed by Feller (1994).

Data Analysis

The data were analysed using Statistica 6 performing ANOVA and Newman-Keuls tests to examine differences between treatments at $P < 0.05$.

Results

Characteristics of the Soils Studied

Morphological Characteristics

All the soils exhibited the same pedogenesis, with iron segregation and were characterized by three horizons (A, Bt1, Bt2), all well drained. Bt2 overlies a petroplinthic horizon (hardpan) with average compaction which limits root penetration. In general the structure is subangular blocky, weakly developed, or indeed massive, with the exception of the organic surface horizon under savannah. There is an increase in clay with depth. The textures vary from sandy loam at the surface to sandy clay at depth. The A horizon is thicker (21.5 cm on average) under savannah than under crops (10 cm). The petroplinthic horizon is shallower under crops (64–67 cm deep) than under savannah (70 cm). In the cultivated soils, the gravel fraction is larger in the surface layers where the proportion of ferruginous gravel is of the order of 33%. The bulk density is lower under savannah, and statistically different notably in the surface layers (Table 1). The soil surface shows signs of water erosion which is very clear on the cultivated plots.

Physicochemical Characteristics of Soils

The analytical results (Table 1) show: (1) textures are similar for the A, Bt1, and Bt2 horizons for the different sites, and the clay fractions increase from top to bottom; and (2) a reduction in the contents of C, N, Ca^{+}, and exchangeable bases for soils under crop. This fall is less important when the manure is brought.

The falls in C content under crops is accompanied by lower CEC values. The tendency towards acidification of the cropland soil is clear, particularly when manure was not applied (Table 1). The Al^{+++} content is higher under crops in the Bt2 horizons, especially with manure where it reaches 0.76 $cmol_c kg^{-1}$ soil. The pH

Table 1. Results of physicochemical analyses of soils

	Savannah			Crop without manure			Crop with manure		
Cover horizon	**A**	*Bt1*	Bt2	**Ap**	*Bt1*	Bt2	**Ap**	*Bt1*	Bt2
Thickness [dm]	**2.15a**	*3.35a*	1.47c	**1.07b**	*2.63a*	2.73ab	**1.05b**	*3.10a*	2.60b
Bulk density [g cm^{-3}]	**1.54c**	*1.64b*	1.72a	**1.76a**	*1.73a*	1.76a	**1.69b**	*1.64b*	1.76a
Texture	**Sandy loam**	*Sandy clay loam*	Sandy clay	**Sandy loam**	*Sandy clay loam*	Sandy clay	**Sandy loam**	*Sandy clay loam*	Sandy clay
Clay [%]	**15.7a**	*43.6a*	47.4a	**14.3b**	*43.6a*	44.9a	**13.2b**	*42.6a*	42.6a
pH (H_2O)	**6.70a**	*6.56a*	6.10a	**6.18b**	*5.90b*	5.60b	**7.15a**	*5.90b*	5.10b
C [mg g^{-1}]	**20.3a**	*4.7a*	3.2a	**5.3c**	*4.6a*	4.0a	**13.0b**	*4.1b*	2.1a
N [mg g^{-1}]	**1.3a**	*0.4a*	**0.3a**	**0.4b**	*0.3a*	0.3a	**1.1a**	*0.4a*	0.2a
C:N	**15.42a**	*12.33a*	12.16a	**14.59b**	*14.34a*	13.44a	**11.95c**	*11.54a*	10.01a
exch. Ca [cmol$^+$ kg^{-1}]	**5.64a**	*1.29a*	1.06a	**1.05c**	*0.78b*	0.69b	**3.02b**	*0.55b*	0.44c
Ca + Mg + K + Na [cmol$^+$ kg^{-1}]	**8.4a**	*3.2a*	2.2a	**1.7c**	*1.2b*	1.1b	**5.4b**	*1.5b*	1.1b
CEC [cmol$^+$ kg^{-1}]	**10.8a**	*3.9a*	3.4a	**1.9c**	*1.7c*	2.1c	**7.6b**	*2.9b*	3.1b
exch K [cmol$^+$ kg^{-1}]	**0.44a**	*0.22a*	0.11b	**0.05a**	*0.04a*	0.09b	**0.69a**	*0.53a*	0.24a
exch. Al [cmol$^+$ kg^{-1}]	**0.00a**	*0.02b*	0.14c	**0.04a**	*0.20ab*	0.49b	**0.00a**	*0.46a*	0.76a
P (Olsen-Dabin) [mg kg^{-1}]	**12.9b**	*9.8a*	10.9a	**6.4c**	*6.3a*	3.55b	**16.0a**	*7a*	4.6b
Saturation	**0.78b**	*0.82a*	0.66a	**0.87a**	*0.71b*	0.54b	**0.71b**	*0.52c*	0.36c

Values are mean of $n = 4$; for the same level of horizon, treatments with the same letter are not statistically different at $p = 0.05$.

(water) in the Bt2 horizon under cropping with manure is the lowest of all the results. With manure, the pH, phosphorus, and exchangeable P are higher at the surface of the cropland than in the other cases (Table 1).

Quantitative Assessment of SOM Changes

Stocks of Soil Carbon

Substantial differences between C contents at the surface can be seen (Figure 1). The savannah shows the highest C content (2.03%). The C contents under cropping without manure are the lowest at the surface and show very little change with depth.

In the deeper horizons, the C contents fall and become uniform for all management methods.

The stocks of C calculated using the IPCC standard (30 cm) show that this layer contains the majority of the C stock: 75% under savannah, 65% under manured cropland, and 53% under unmanured cropland (Table 2).

Qualitative Assessment of SOM Changes

Soil C/N

C/N ratios on average lie between 10 and 15 and are as expected in this zone (BUNASOLS, 1999). Over all the results, the ratio decreases with depth (Table 3). Under crops and at the surface, despite the virtual absence of fresh organic material applications under the crops without manure, the C/N ratio (14.6) is similar to that found under savannah (15.4).

Particle Size Distribution of the SOM

C and N Contents of the Fractions

The results of particle size fractionation are presented in a synthetic diagram which shows several fractions on the same graph. In this graphic representation, the

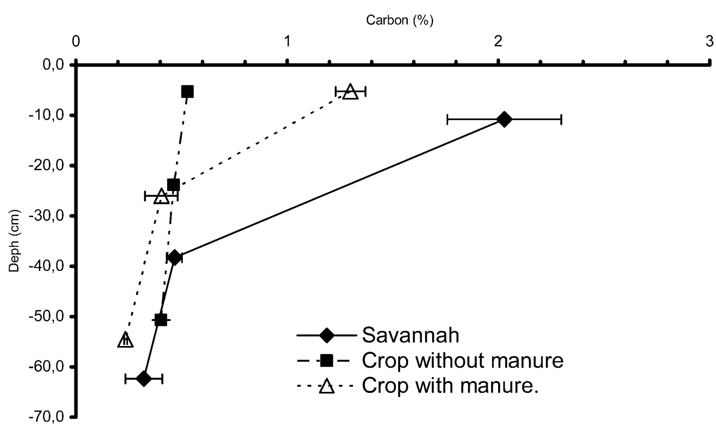

Figure 1. Carbon profiles using midpoints (%). Bar = standard error of mean (SE).

Table 2. Stocks of carbon (Mg ha^{-1})

Horizons	Savannah	Crop without manure	Crop with manure
A	56.5 (*69*)	5.2 (*17*)	13.1 (*34*)
Bt1	20.1 (*25*)	14.6 (*49*)	17.6 (*46*)
Bt2	5.2 (*6*)	10.3 (*34*)	7.4 (*19*)
0–30 cm	61.5 (*75*)	15.9 (*53*)	24.7 (*65*)
Ct (hardpan)	82	30	39

(X): Proportion of C of the horizon compared to total carbon (Ct).
Ct: Total stock of C above the hardpan.

abscissa is the sum of all the fractions, from left (the smallest) to right (the greatest). Ordinate is the value (C %) of the fraction. This representation is chosen to allow a spacing of points.

A Horizon. In the 200–2000 µm fractions (Figure 2) the C contents vary according to the management method. These fractions contain 20% of the total C (Ct) under savannah, 16% under crops with manure, and only 15% under unmanured crops (Table 4).

In the 20 and 200 µm fractions, the lowest C contents were recorded and under the crop without manure, the lowest of all. In the 0–20 µm fractions, clear differences were noted between the three management methods. The C contents of these fractions are the highest compared with other fractions. In the A horizon, they contain 49–69% of Ct.

The N contents are generally in proportion to those of C, except for the 20–200 µm fractions where, under the unmanured cropland, they were slightly higher than those observed under savannah. In all the fractions, in this horizon, the N content was homogeneous for the manured crop and the savannah. The N content for the unmanured cropland are clearly the lowest.

The variations in C and N contents according to the management method are mainly seen in the A horizon (Figure 2).

Bt2 Horizon

In general, the C and N contents of Bt2 (Figure 3) are lower than those of A (Figure 2). In the 200–2000 µm fractions, the contents are highest under manured crops. The C contents of these fractions represent 12% under savannah, 10% under manured crops, and 9% under unmanured crops. In the Bt1 horizon, these fractions contain 14% of Ct under unmanured crops, 12% under savannah and 8% under manured crops.

Table 3. C/N ratios

Horizons	A	Bt1	Bt2
Savannah	15.4	12.3	12.6
Crops with manure	12.0	11.5	10.0
Crops without manure	14.6	14.3	13.4

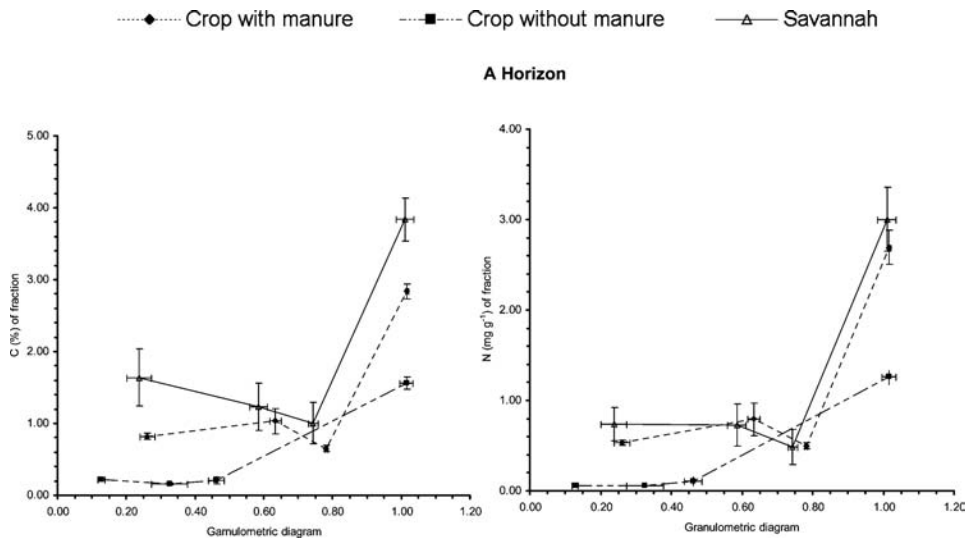

Figure 2. C and N contents of the fractions (A horizon). This graphic representation has the aim to give, in one figure, all the results of the organic matter fractionation. To improve the legibility of the graph, the cumulated proportion allocated to the fractions, from the greatest one (left) to the smallest one (right) are presented on the abscissa, from the left to the right. On the ordinate is presented the C % of each fraction. For every point of the graph is given the standard deviation of (a) C %, as a vertical bar, and (b) of the proportion of the fraction as a horizontal bar.

In the 20–200 μm fractions the contents are all the same. In the fine fractions (0–20 μm) the highest C contents were obtained under unmanured crops.

The N contents: (1) in the 200–2000 μm fractions are highest under manured crops; (2) are uniform in the 50–200 μm fraction; and (3) are higher in the 0–20 μm fractions under crops without manure than under savannah or under manured crops.

In general, the 20–50 μm fractions have the lowest C and N contents whatever the management method and whichever horizon is considered. The values are uniform, notably in Bt1 and Bt2 (3–4% of Ct) for all methods of management.

On the other hand, the 0–20 μm fractions for every horizon have the highest contents of these two elements (Figure 3). In the Bt1 and Bt2 horizons they contain 74% (Bt1 under unmanured crops) to 83% (Bt1 under manured crops) of Ct.

C/N Ratios

The results (Figure 4) show that the C/N ratios decrease consistently, with particle size between the 200–2000 μm fraction and the 0–20 μm fraction.

Discussion

The soils studied are of the same pedological type. They also have the same particle size characteristics. In the absence of a texture effect, one may therefore draw conclusions about the effect of the method of management of C and N accumulation in these soils. Assuming that these soils were uniform to begin with, the results indicate that the stocks of organic C have decreased greatly during 13 yr after clearing as a

Table 4. Carbon content of fractions compared to total carbon (%)

	A			Bt1			Bt2		
Horizon	Savannah	Crop with manure	Crop without manure	Savannah	Crop with manure	Crop without manure	Savannah	Crop with manure	Crop without manure
200–2000 μm	20	16	15	12	8	14	12	10	9
50–200 μm	21	28	10	8	6	9	9	8	9
20–50 μm	8	7	5	3	4	3	4	3	4
0–20 μm	51	49	70	77	82	74	75	79	78

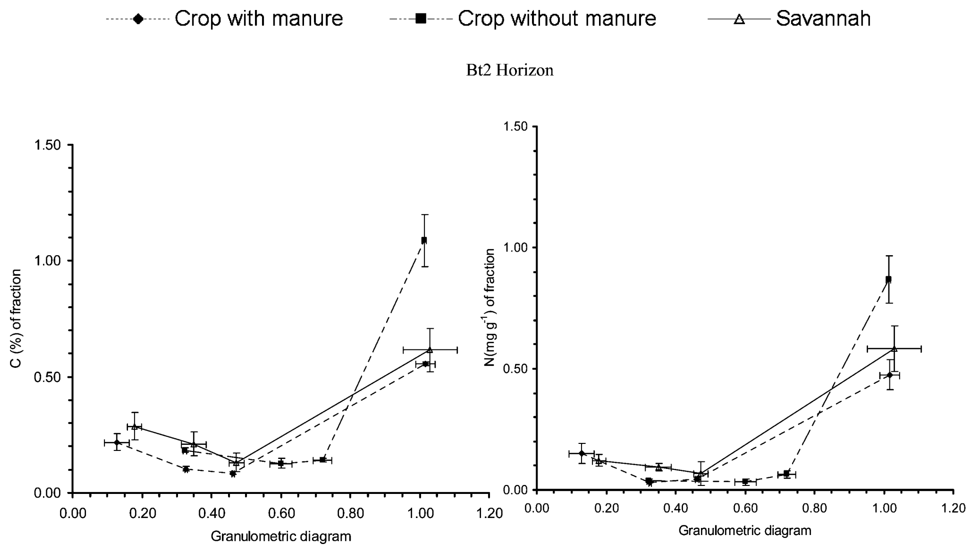

Figure 3. C and N contents of the fractions (Bt2). For the graph representation explanation see note for Figure 2.

result of cultivation without organic manure: from 82 Mg C ha^{-1} under savannah, the C stock fell to 38 Mg C ha^{-1} with organic manure and to 30 Mg C ha^{-1} under unmanured cropping in the 120 cm profile for example and from 61 Mg C ha^{-1} under savannah, to 25 Mg C ha^{-1} with organic manure, and to 16 Mg C ha^{-1} under unmanured crops for the surface 30 cm depth. The fact that this savannah is partially destroyed or exploited every year by bush fires and communal grazing indicates that the potential storage of C in the soil is probably more than 82 Mg ha^{-1}; in Sub-Saharan Africa, biomass burning significantly reduces SOC in the upper centimetres

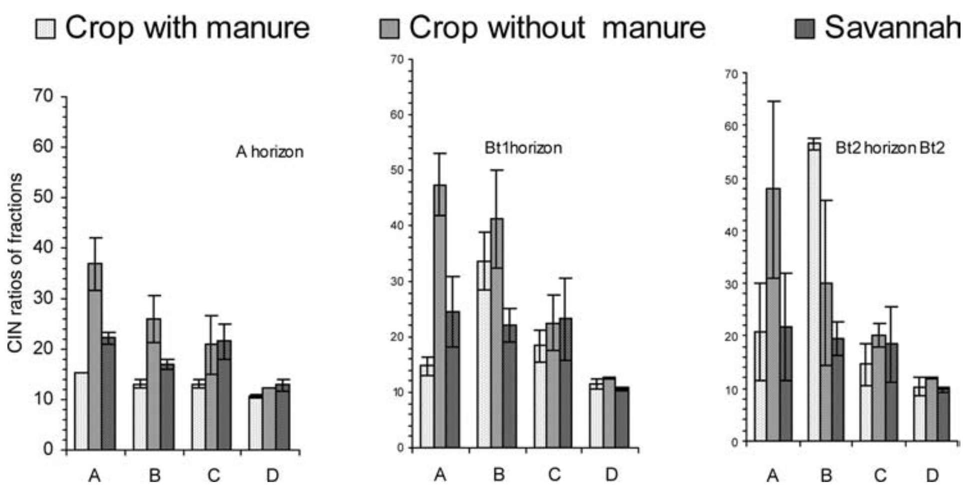

Figure 4. C/N ratios of the fractions. Bar = standard error of mean (SE) (A: 200–2000 µm fractions; B: 50–200 µm fractions; C: 20–50 µm fractions; D: 0–20 µm).

of soil (Vagen et al., 2005). The application of manure results in a SOC content that is 9 Mg C ha^{-1} higher than in unmanured plots. This effect of FYM is small and could be increased by increasing the amount and changing the quality of the manure by improving the humification of the manure. Berger et al. (1987) recommend rates of 5–6 Mg DM ha^{-1} of FYM in this zone to maintain a satisfactory humic balance, but this would require an increase in the herd size which would not be feasible with the local forage resources.

The main influence of the different management systems is on the C contents of horizons A and Bt1. As a result of introducing cropping, the changes are especially marked in the surface horizons. In cropping with no added manure, the A horizons loose the most SOM: 50 t ha^{-1} as a result of cropping.

Taken as a whole, the results of particle size analysis of the SOM show that all the fractions exhibit variations in C content, but the degree of change depends on the fraction and the management method.

The C and N contents of the 0–20 μm fractions are the highest. In horizon A, at least 49% of the total C is contained in these fractions. In horizons Bt1 and Bt2 these fractions contain 74–83% of the total C. The SOM is therefore stored mostly in these fractions. The unmanured crop results in a serious lowering of the C and N contents in the 0–20 μm fractions of the A horizon.

The contents of the fractions 20–50 μm and 50–200 μm are usually the lowest, and are similar for all management systems and horizons. We can therefore say that these fractions, particularly those between 20 and 50 μm contribute little to the SOM stock.

In the 200–2000 μm fractions the C and N contents are variable in the A horizons. The decrease observed may be attributed both to the lower returns of OM and the rapid turnover in these fractions, which is accelerated by soil tillage (Feller and Beare, 1997).

Clearing and cropping continue to lead to big reductions in C and N contents in the coarse and fine fractions of the A horizons. The scheme suggested by Feller & Beare (1997) for clayey soils (with large variations in the clay fractions) is thus verified: "in coarse-textured soils a significant proportion of SOC dynamics are due to changes associated with the sand-size fraction (i.e., particulate organic matter). In contrast, much of the variation in SOC in fine textured soils, especially those with high clay content was associated with 0–2 μm fraction. These results imply that a significant proportion (30–40%) of the SOC associated with clay fraction is relatively labile.

The C/N ratio of the soil decreases with depth, indicating greater maturity of the humus in the deeper horizons. But does the soil management influence these C/N ratios? In the case of the site cultivated without manure application, the C/N ratios are higher than on the site cultivated with manure applied. This might be explained by the fact that the N applications to this field are nil except for atmospheric deposition and fixation of free N_2. The only organic applications are those of the root biomass of millet whose C/N ratio is relatively high, about 50 (Chopart, 1999).

As a result of manure application, apart from the increase in C content at the surface, there is a fall in the C/N ratio which is explained: (a) by an N application due to manure, and (b) by humification and rapid mineralization of feces and other plant debris under cropping with manure.

The C/N ratios of the fractions decrease steadily, from the 200–2000 μm fractions to the 0–20 μm fractions. These results, associated with morphological observations, suggest that the 200–2000 μm fractions contain the most organic matter in the

form of plant debris. The <20 µm fractions have low C/N ratios. Chistensen (1992) shows that the organic mater of the fine fractions contains microbial residues rich in N what explains low C/N ratios.

According to Feller (1994) the <20 µm fractions however contain organic matter of an organomineral nature, with a more advanced degree of evolution.

Agronomically, there is a tendency towards acidification after clearing the bush (Pieri, 1992). This increases the solubility of Al^{+++}, reduces the availability of P due to the release of Al^{+++} ions and very probably a disturbance of biological activity. The low pH (5.1) observed in Bt2 under manured crops is worthy of mention. There appears to be a favorable effect of manure on rooting and N mineralization in Bt2, which results in a loss of divalent cations by root absorption and lateral transport, the accompanying anion being NO_3^-. But in the A horizon, the sum of all basic cations (Ca + Mg + Na + K) is higher in manured soil than unmanured. The use of manure seems to be a good practice to control soil acidification of cultivated soils. As acidification is a process resulting from the introduction of cropping, soil amendments such as liming and natural phosphates are recommended in addition to manure so as to optimize the effect of the manure on soil fertility and on the SOM stock. Phosphate concentration of the A horizon in manured soil (Table 1) is significaly higher than in the savannah soil (16 vs. 13 mg kg^{-1}). This result shows that manure, even at the low rate used, seems to be effective at maintaining soil P.

Apart from a slight thinning of the A horizon and of the whole of the soil profile under cropping, the increase in coarse particles, especially in the surface horizons, indicates that erosion is occurring. Surface runoff under cropping at the beginning of the rainy season can be considerable and in the absence of a crop cover can cause great damage. As a result of the progressive loss of SOM during the years following the introduction of cropping without any replacement of the organic matter, the soils become particularly sensitive to erosion. The adoption of practices aimed at reducing these erosion losses (stone rows, contour ridging) can help to restore the SOM.

Conclusions

In conclusion, this study shows that the soil organic carbon storage potential is about 62 Mg ha^{-1} in the surface 30 cm depth in this area. For reducing the losses of C and regenerating the SOM under cropping, the following factors may be regarded as important: (1) choose crops with a good root system and apply organic manures which are resistant to rapid biodegradation, (2) reduce tillage to avoid creating conditions for rapid biodegradation, (3) to prevent erosion of the coarse SOM at the surface by ridging and stone bunds etc., (4) practice regular liming.

References

Arrouays D., J. Balesdent, J. C. Germon, P. A. Javet, J. F. Soussana, and P. Stengel. 2002. *Stocker du Carbone Dans Les Sols Agricoles de France?* Expertise scientifique collective, INRA, Paris.

Batjes, N. H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47:151–163.

Berger, M., P. C. Belem, D. Dakouo, and V. Hien. 1987. Le maintien de la fertilité des sols dans l'Ouest de Burkina Faso et la nécessité de l'association agriculture-élevage. *Coton et Fibres tropicales* 42:201–207.

Bernoux, M., D. Arrouays, C. Cerri, P. M. de Alencastro Graça, B. Volkoff, and J. Trichet. 1998. Estimation des stocks de carbone des sols du Rondônia (Amazonie brésilienne). *Etude et Gestion des Sols* 5:31–42.

BRGM. 1992. *Carte géologique Du Burkina Faso.* BRGM, Paris.

BUNASOLS. 1999. *Etude morphopédologique Des Provinces Du Poni et du Noumbiel*. Rapport Technique, BUNASOLS, Ouagadougou.

Chopart, J. L. 1999. Relation entre état physique du sol, systèmes racinaires et fonctionnement hydrique du peuplement végétal. Doctorat, Université Joseph Fourrier-Grenoble 1, Grenoble.

Christensen, B. T. 1992. Physical fractionation of soil and organic matter in primary particle-size and density separates. *Advances in Soil Science* 20:1–90.

CPCS. 1967. *Classification des sols. Travaux de la Commission de Pédologie et de Cartographie des Sols* (1963–1967). ENSA-Grignon, Laboratoire de Pédologie-Géologie, Paris.

Detwiler, R. P. 1986. Land use change and the global carbon cycle: The role of tropical soils. *Biogeochemistry* 2:67–93.

Dugué, P. 1993. La gestion de la fertilité et l'utilisation des ressources naturelles dans les systèmes agro-pastoraux soudano-sahéliens, in *Journée AGER: Gestion De La Fertilité*. CIRDD, Montpellier, France.

Dugué, P. 1994. Stratégie des producteurs et gestion des ressources naturelles en Afrique soudano-sahélienne, in *Recherche-Système en Agriculture et Développement Rural.* (Systems-Oriented Research in Agriculture and Rural Development). Symposium International, CIRAD, Montpellier, France.

Eswaran, H., E. van den Berg, and P. Reich. 1993. Organic carbon in soils of the world. *Soil Science Society of America Journal* 57:192–194.

FAO, ISRIC and AISS. 1999. *Base De Référence Mondiale Pour Les Ressources en Sols (WRB)*. Rep. No. 84. FAO, Rome.

Feller, C. 1994. La matière organique dans les sols tropicaux à argile 1:1. Recherche de compartiments organiques fonctionnels. Une approche granulométrique. Doctorat Sciences Naturelles, Institut de Géologie de Strasbourg.

Feller, C. and M. H. Beare. 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79:69–116.

Guinko, S. 1998. Caractéristiques de la végétation du Burkina Faso et leurs impacts sur les sols. in 16è Congrès Mondial de science du sol (Tour B7), Ouagadougou-Abidjan. Association Ouest et Centre Africaine de Science du Sol.

Hien, E. 2004. Dynamique du carbone dans un Acrisol ferrique du centre ouest Burkina: Influence des pratiques culturales sur le stock et la qualité de la matière organique. Thèse de Doctorat, ENSAM, Montpellier, 138 p.

Houghton, R. A., D. L. Skole, and D. S. Lefowitz. 1991. Change in the landscape of Latin America between 1850 and 1985, II. Net release of CO_2 to the atmosphere. *Forest Ecology Management* 38:173–199.

Lundgren, B. O. 1978. *Soil conditions and nutrient cycling under natural and plantation forests in Tanzanian highlands*. Rep. No. 31. Department of Forestry Soils, Swedish University of Agricultural Sciences, Uppsala.

Mckenzie, N., P. Ryan, P. Fogarty, and J. Wood. 2000. *Sampling, measurement and analytical protocols for carbon estimation in soil, litter and coarse woody debris.* Rep. No. 14. National Carbon Accounting System Technical Report (Australian Greenhouse Office).

Pieri, C. 1989. *Fertilité des terres des savanes.* Ministère de la Coopération-CIRAD, Paris.

Pieri, C. 1992. *Fertility of Soils: A Future for Farming in the West African Savannah*. Springer Series in Physical Environment, Springer-Verlag, Berlin.

Sanchez, P. A., C. A. Palm, L. T. Szott, E. Cuevas, and R. Lal. 1989. Organic input management in tropical agroecosystems, pp. 125–152, in D. C. Coleman, J. M. Oades, and G. Uehara eds., *Dynamics of soil organic matter in tropical ecosystems*. Niftal Project, Univ. of Hawaii.

Shang, C., and H. Tiessen. 1998. Organic matter stabilization in two semiarid tropical soils: size, density, and magnetic separations. *Soil Science Society of America Journal* 62:1247–1257.

Vagen, T.-G., R. Lal, and B. R. Singh. 2005. Soil carbon sequestration in sub-saharan Africa: A review. *Land Degradation & Development* 16:53–71.

Van Noordwijk, M., C. Cerri, P. L. Woomer, K. Nugroho, and M. Bernoux. 1997. Soil carbon dynamics in the humid tropical forest zone. *Geoderma* 79:187–225.

Volkoff, B., C. Cerri, and F. Andreux. 1989. Matière organique et conservation des sols en zones tropicales forestières: Voies actuelles de recherche, in FAO, ed., *Neuvième réunion du sous Comité Ouest et Centre Africain de Corrélation des Sols pour la mise en valeur des terres*. Rome. FAO.

Zech, W., N. Senesi, G. Guggenberger, K. Kaiser, J. Lehmann, T.M. Miano, A. Miltner, and G. Schroth. 1997. Factors controlling humification and mineralisation of soil organic matter in the tropics. *Geoderma* 79:117–161.